

THE MOST ENERGETIC PARTICLES IN THE UNIVERSE

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Several issues related to the lensing of ultra-high energy cosmic rays by the Galactic magnetic field are discussed.

The spectrum of the cosmic rays (CRs) arriving to the Earth has the overall shape of a leg, with a knee at 10^{16} eV beyond which it becomes steeper and an ankle at $\sim 5 \times 10^{18}$ eV where it becomes harder again up to the highest energies observed of 3×10^{20} eV. The region beyond the ankle, i.e. the foot of the spectrum, is attracting renewed interest nowadays with the deployment of large detectors, such as HiRes and Auger, which are expected to find an answer to several issues raised by the observation of such energetic events. These are:

- i)* The production mechanism giving rise to such enormous energies (relativistic Fermi acceleration, production in decays of topological defects or heavy relics from the big bang, etc.).
- ii)* The nature of the primaries, i.e. whether they are protons, nuclei, γ rays, neutrinos with new interactions or more exotic objects (see Berezhinsky's talk).
- iii)* How they manage to propagate from their sources up to us, since for instance protons are attenuated by photopion production off the CMB photons at energies above 5×10^{19} eV¹, and similarly nuclei can photodisintegrate through interactions with CMB and IR photons². Through these processes 'hadronic' CRs with energies above 10^{20} eV would lose their energy in a few dozens of Mpc, leading to the famous GZK cutoff which was expected, but not observed, in the CR spectrum.
- iv)* The location of the sources, i.e. if CRs are produced in the Galaxy, if they are extragalactic (e.g. produced in active galaxies) or uniformly spread through cosmological distances, as in some topological defect models.

It is widely believed that below the ankle CRs are protons or nuclei mostly of galactic origin. Since the gyroradius of a CR with energy E and charge Z in a magnetic field B is $R \sim \text{kpc}(\mu G/B)(E/Z 10^{18} \text{eV})$, below the ankle the CR trajectories are very curly for the galactic fields of a few μG and one has to describe the propagation in terms of diffusion and drift. However, above the

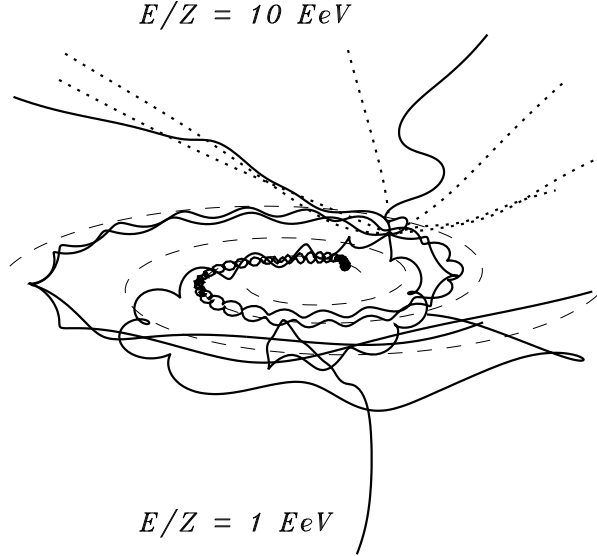


Figure 1. Examples of trajectories of nuclei with $E/Z = 1 \text{ EeV}$ ($= 10^{18} \text{ eV}$) and 10 EeV . At the lower energies particles start to be trapped by the spiral structure of the regular galactic magnetic field.

anle the gyroradii become comparable or larger than the scale of the galactic magnetic field, so that trajectories are straighter and one can start to speak of small CR deflections due to the magnetic fields. In particular one expects to be able to roughly trace back the location of the sources, and hence to do astronomy, with the highest energy events (see fig. 1).

The lack of any obvious observed anisotropy towards the galactic plane then suggests that in the ‘foot’ of the spectrum CRs are most likely extragalactic (see however de Rújula’s talk). In this case, if CRs are indeed normal hadronic matter (nuclei or protons) the sources should not be too far (i.e. less than 20-50 Mpc). Correlations of the observed arrival directions with the location of candidate sources or with the general direction of the supergalactic plane have been searched for (but with no clear evidence of correlations found yet however). When looking for the source locations it is important to correct for possible magnetic deflections using plausible models of the Galactic magnetic fields ^{3,4}, and eventually also of extragalactic ones if these were to turn

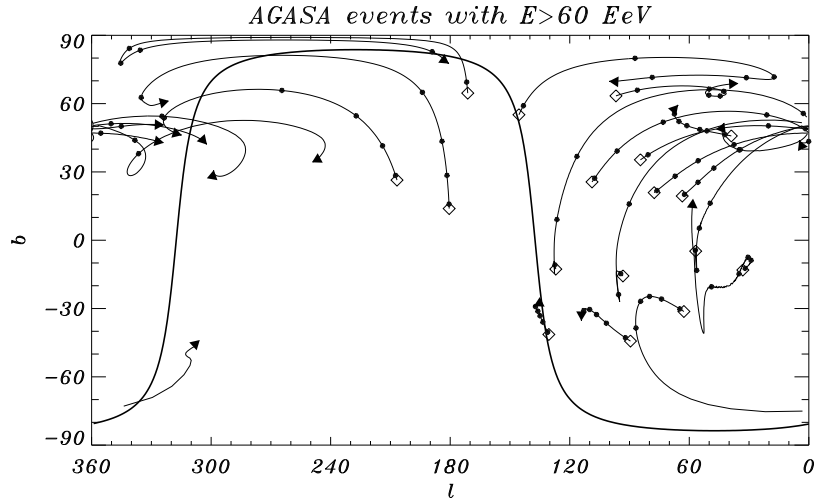


Figure 2. Observed arrival directions (diamonds) of AGASA events with energies $> 6 \times 10^{19}$ eV and the corresponding incoming directions outside the Galaxy for different CR charge Z . The dots along the lines indicate the results for $Z = 1, 6, 10, 14$ and 20 and the tip of the arrow is for $Z = 26$ (iron).

out to be very large⁵. For instance, fig. 2 shows the directions of arrival to the halo of the highest energy events recorded by AGASA assuming different CR compositions, from protons up to Fe nuclei, adopting a bisymmetric spiral model for the galactic magnetic field⁴. Clearly the deflections are sizeable even at these energies if CRs are heavy nuclei. To do detailed CR astronomy would require then to know the CR composition to some extent.

As we have shown^{4,6} magnetic deflections produce other important effects which are even more striking. Indeed, the galactic magnetic field acts as a giant lens and can magnify sizeably the CR fluxes coming from any given source. Since the deflections are energy dependent, this lensing effect will modify the original spectrum of the source. Furthermore, since the B fields are not homogeneous, CRs from one source may arrive, for a given energy, through more than one path, i.e. multiple images of a source can be seen (fig. 3). The new images appear in pairs (of opposite parity) along critical lines in the sky seen on Earth, corresponding to caustic lines in the source sky. When the source is on a caustic, the magnification of the new pair of images is

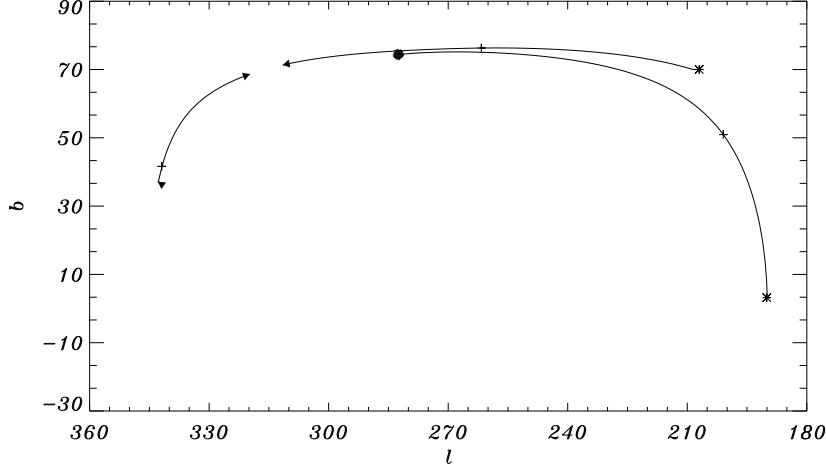


Figure 3. Illustration of the angular displacement of the image of a source with energy and of the formation of secondary images in pairs. The actual source (big dot) is in the direction of M87. The secondary images appear where the two arrows meet. The images are located at the plus signs for $E/Z = 10^{19}$ eV and at the asterisks for $E/Z = 5 \times 10^{18}$ eV.

divergent, but for decreasing energies the caustic moves away from the source and the magnification behaves as $\mu_i \simeq A/\sqrt{1 - E/E_0} \pm B + C_i\sqrt{1 - E/E_0}$ near the energy E_0 at which the pair of images appeared ⁶ (see fig. 4).

When convoluted with a continuous energy spectrum the divergence at the caustic is smoothed out, but anyhow the large magnifications achieved make it more likely to detect events at those energies. This may be helpful to account for some of the doublets and triplets which have been observed, which actually tend to be very close in energy as would be expected from clustering near a caustic.

There are many analogies^{4,6} between the features of magnetic lensing and the more established gravitational lensing effect. This last is of course achromatic, so that instead of changing the energy as in our discussion above the analog would be to displace the source.

The lensing effect can also modify the average composition arriving to the Earth, since for a given energy the magnification of the fluxes depends on the charge of the CR nuclei. Also significant time delays result from the deflections which can be relevant in the observation of bursting sources.

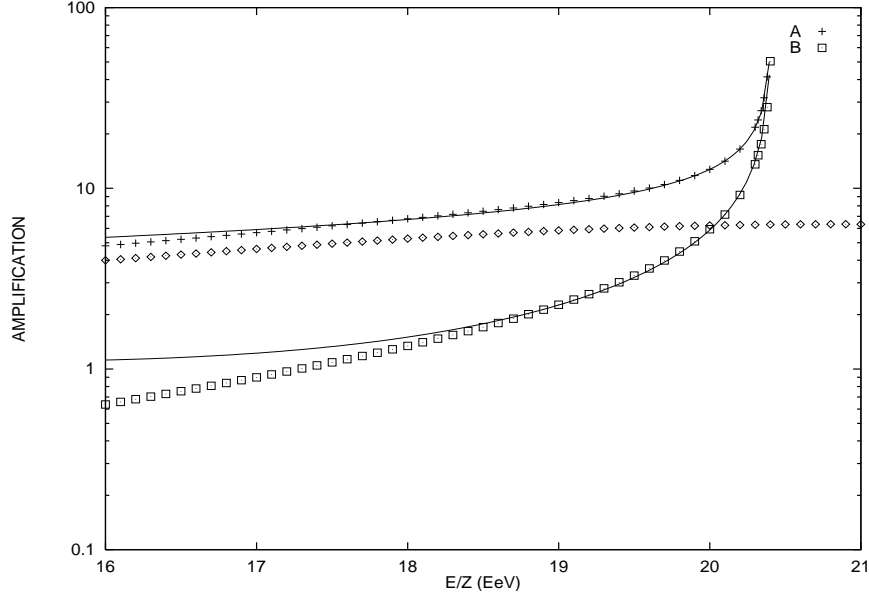


Figure 4. Numerical results and analytic fits to the magnification of the CR flux near a caustic, where two images appear, together with the original image (diamonds), for a source located in the direction of M87 in the Virgo Cluster.

All these effects are important if the ultra high energy CR sky is dominated by a few powerful sources, as would be expected in AGN models. If the CR flux were instead approximately isotropic (as happens at lower energies), the Liouville theorem⁷ would preclude the observation of any lensing effect: when a region of the sky is magnified, it is also seen through a larger solid angle and the flux per unit solid angle remains constant. Remarkably, the transition from one regime to the other seems to be precisely around the ankle of the CR spectrum so that a host of interesting effects may be studied with the expected increase in statistics at the end of the CR spectrum.

Acknowledgments

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